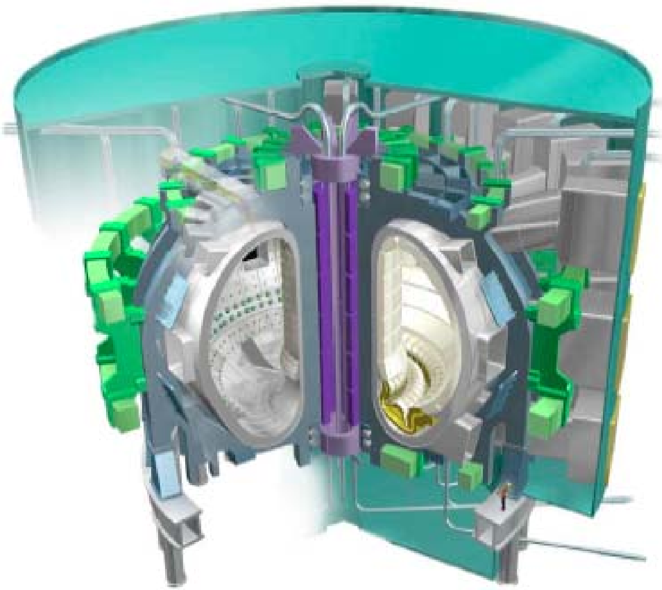
Theory and Simulation: Recent Highlights

William M. Nevins,

Bruce I. Cohen, and Ronald H. Cohen, LLNL

and the U.S. Magnetic Fusion Theory Community



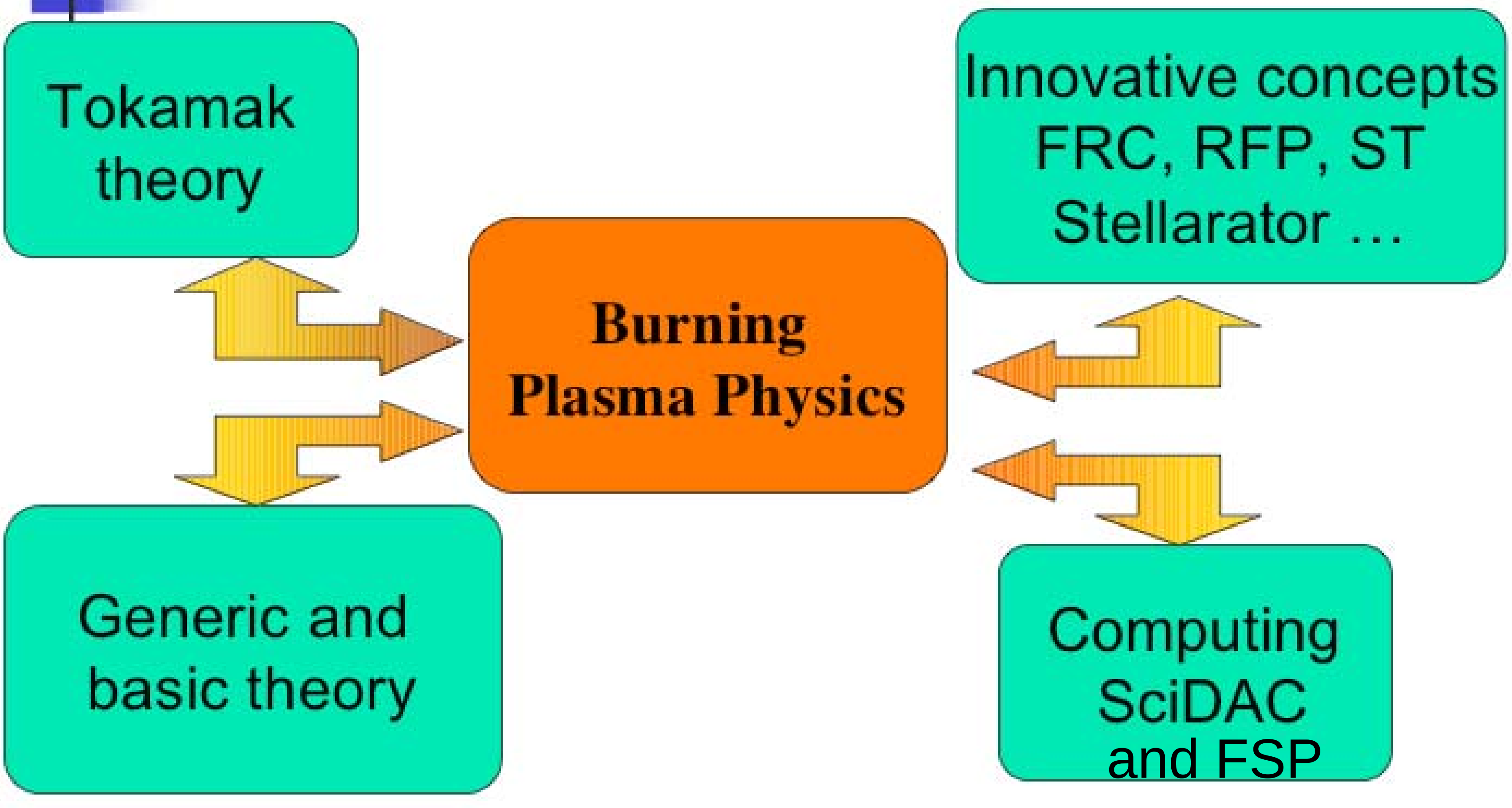
Representing the Theory Coordinating Committee

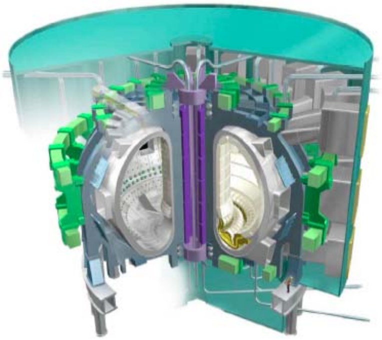
http://web.gat.com/theory/tcc/

Budget Planning Meeting,
March 12, 2008

Supported by Office of Fusion Energy Sciences — Excellent Science Attractive Energy — *Office of Science*

Focus of this talk is on a subset of the theory program





Burning plasma physics modeling challenges and needs

- Modeling approaches
  - Analytic theory
    - Improved models for implimentation in physics codes (e.g., gyro-fluid and gyro-kinetic equations)
    - Analytic solutions where possible
  - Detailed physics codes
    - Qualifying models (is it applicable to burning plasmas)
    - Verifying codes (does the code correctly impliment the model)
    - Validating models (does it reproduce experimental results)
  - Integrated modeling
    - Coupling detailed physics models from multiple topical areas

    $\Rightarrow$ Realistic modeling of tokamak discharges
- Challenging aspects
  - Multiple space/time scales
  - Strong nonlinearities $\Rightarrow$ Stochasticity and turbulence
  - Complicated geometry
  - High-dimensional parameter space (ν^*, $T_e/T_{i,}$, Z_{eff}, …)

Many exciting burning plasma research challenges exist now

Jim Van Dam, 2007 APS DPP Tutorial

National Academies NRC Burning Plasma Report

Burning Plasma Research Opportunities in Next Decade:

- Understand dynamics of edge Pedestal region
- Physics and control of Edge-Localized Modes
- Stabilization of neoclassical tearing modes
- Develop steady-state & advanced tokamak regimes
- The density limit and high density operation
- Turbulence and transport
- Disruption avoidance and mitigation
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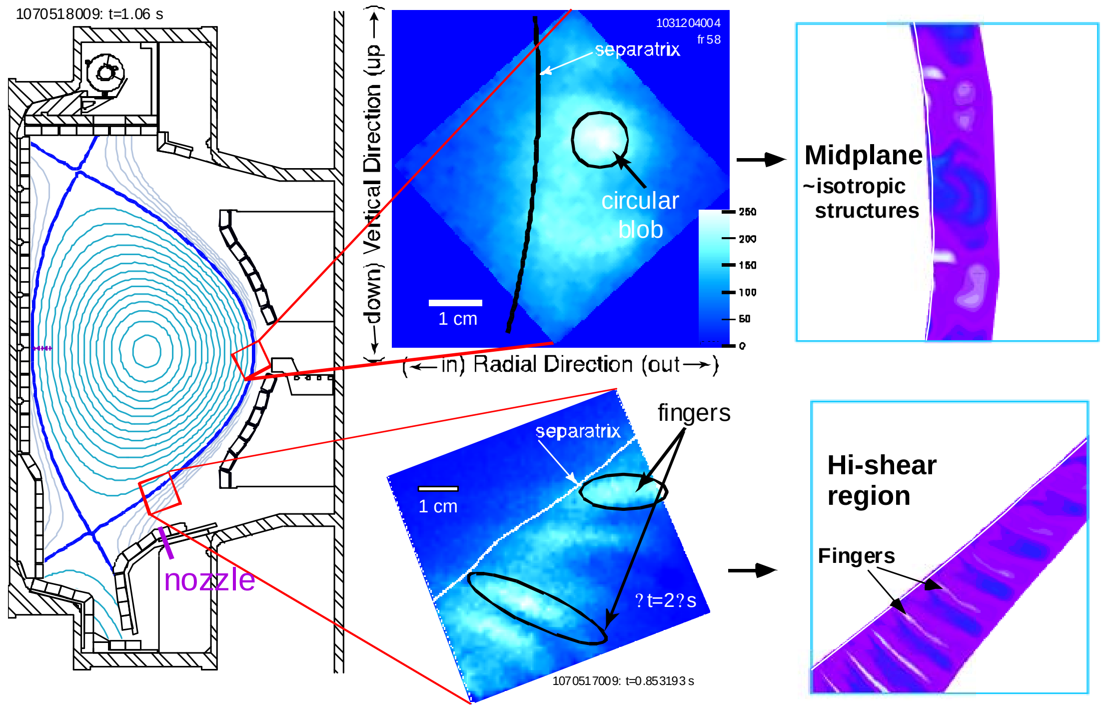
Edge turbulence validation: 3D fluid BOUT shows “blob” fingers seen by near-X-point GPI in C-Mod

- Characterizing edge turbulence & transport is needed to predict L-H transition & peak power to ITER divertor
- Elongated propagating SOL blobs in C-Mod near X-pt are reproduced by BOUT, which includes detailed magnetic shear
- Analysis shows that flux-tube distortion from magnetic shear can explain the structures

Alcator C-Mod configuration

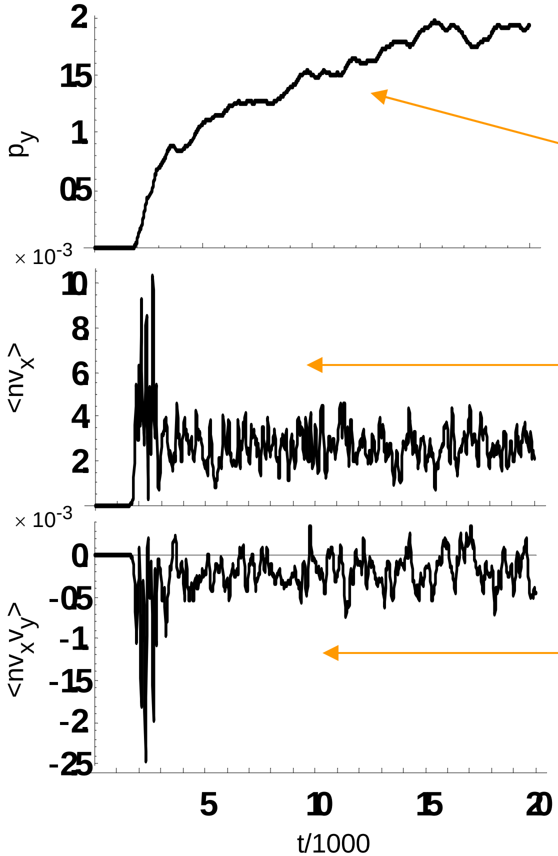
Turbulence imaging via Gas Puff Imaging (MIT, PPPL)

BOUT turbulence simulations (density contours; LLNL)



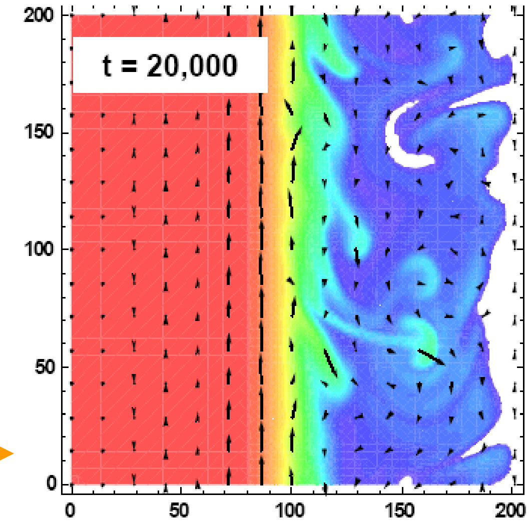
Result builds confidence in our detailed understanding of key processes in SOL turbulence and transport that can be used to better predict ITER heat fluxes

Dynamics of edge turbulence, sheared flows, and blobs: poloidal momentum transport



Total poloidal momentum in simulation increases with time (due to sheath momentum absorption).

Particle flux across LCS shows particle transport by blob ejection.



Poloidal momentum transport at LCS due to blobs and Reynold's stress.

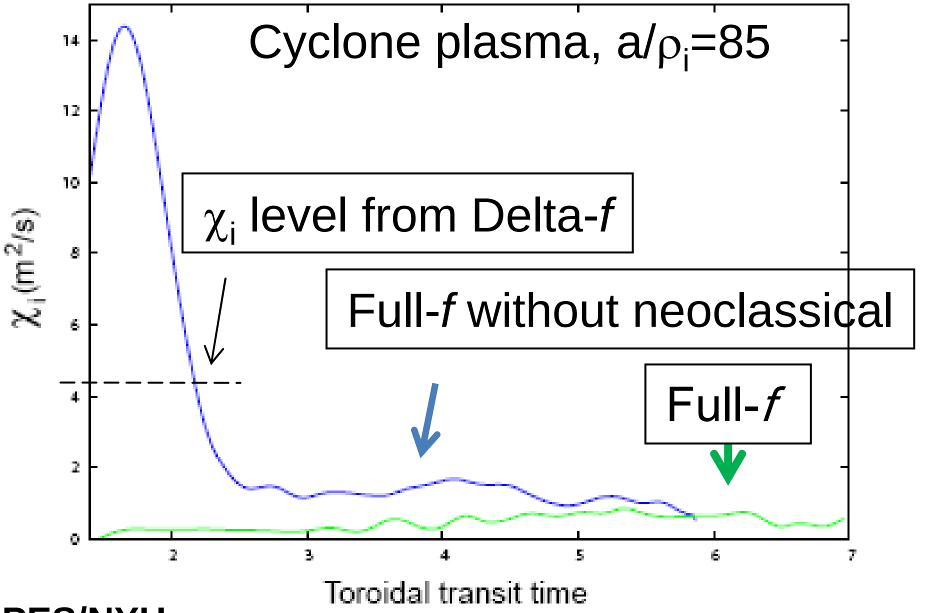
Poloidal momentum transport into SOL can spin up core and create edge velocity shear layers.

SOLT code: Myra et al., PoP (2008)

Full-*f* gyrokinetic particle simulation of plasma edge

SciDAC Proto-FSP Center for Plasma Edge Simulation

- Full-*f* simulation is more difficult than conventional delta-f
- Delta-*f* technique is not applicable to edge plasma
  - Neutral particle source and loss to wall
  - Strong neoclassical physics interacts with turbulence
- Even in core plasma, full-*f* is needed to simulate nonlinear neoclassical and turbulence interaction self-consistently



We have succeeded in core full-*f*

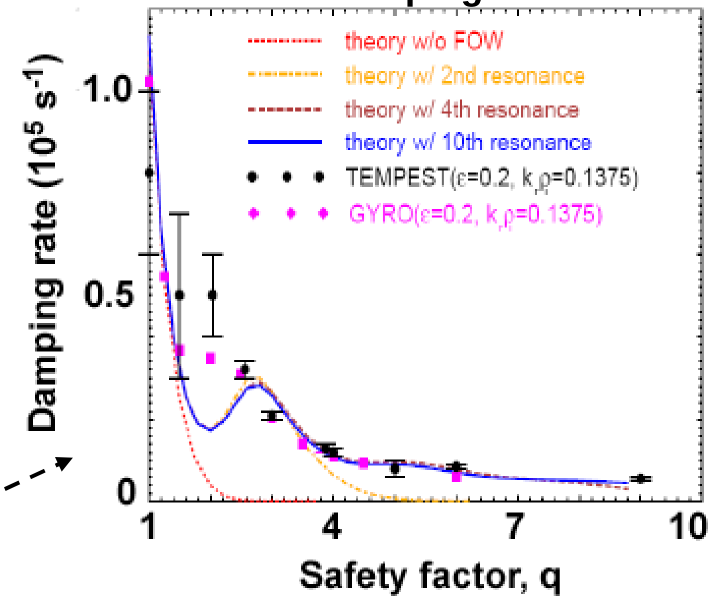
- Neoclassical and ITG turbulence are fully self-consistent
- Small streamers are formed due to nonlinear turbulence interaction with background **ExB**
- Streamers appear if background interaction is suppressed
- We will simulate edge after verification and validation in core

Verification of Full-*f* gyrokinetic continuum simulations

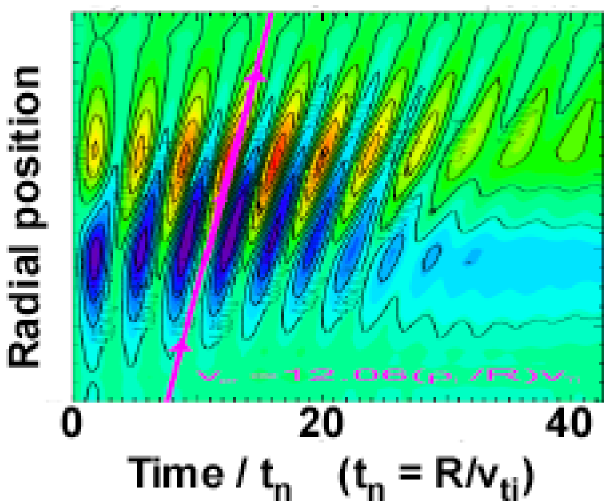
Edge simulation Laboratory

- Verification exercise: Comparing geodesic-acoustic mode dispersion relation as seen in TEMPEST and GYRO
- ITER's low collisionality and high edge *q* make GAMs important to suppressing edge turbulence. L-H transition and H-mode transport will be affected
- Previous theory predicted very small damping at high *q*; new simulations and recent theory (Gao) show high-order transit resonances important to damping
- BES measurements in hot edge of DIII-D show GAM structure that may be explained by damping *q*-dependence and GAM propagation, as seen by TEMPEST and predicted by theory [Itoh et al, (2006)]

GAM damping rate

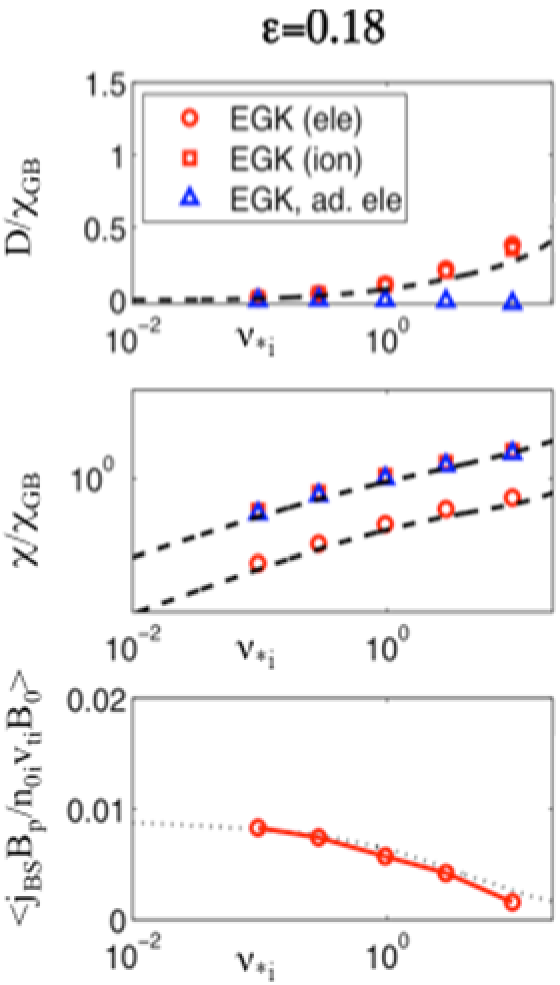


Perturbed density; propagating GAM

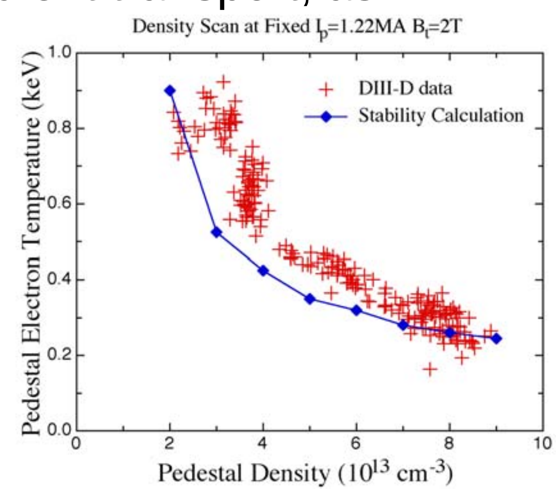


Fundamental Pedestal Height and Width Physics Is Being Studied

- Pedestal height/width based on peeling-ballooning
  - Peeling-Ballooning theory successful in predicting pedestal height given the pedestal width [$\beta_{Nped} \sim \Delta^{3/4}$ f(shape, ν_*,q…)]:
  - Using observed pedestal power dependence and pedestal database, a candidate width model developed $\Delta_{\psi_N} = 0.08\beta_{pped}^{1/2}$
- TGLF transport model includes much of the important physics for pedestal transport
  - Additional benchmarking with GYRO, possible extensions
  - Quantify whether ExB suppression can explain observed width
- Edge-specific gyrokinetic codes being developed to study transport
  - EGK and TEMPEST (ESL project): developing standard efficient tool for neoclassical transport
  - ESL will later address turbulent transport, as will CPES project (XGC code)



Dashed lines → Hinton-Hazeltine[5]
Dotted lines → Sauter et al.[6]



Peeling-ballooning stability

General Atomics/ESL

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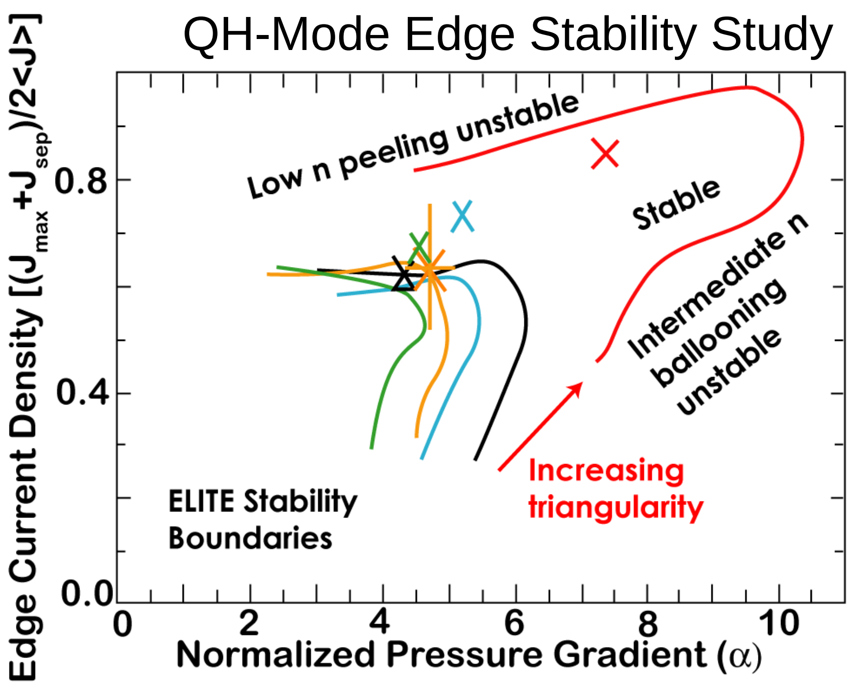
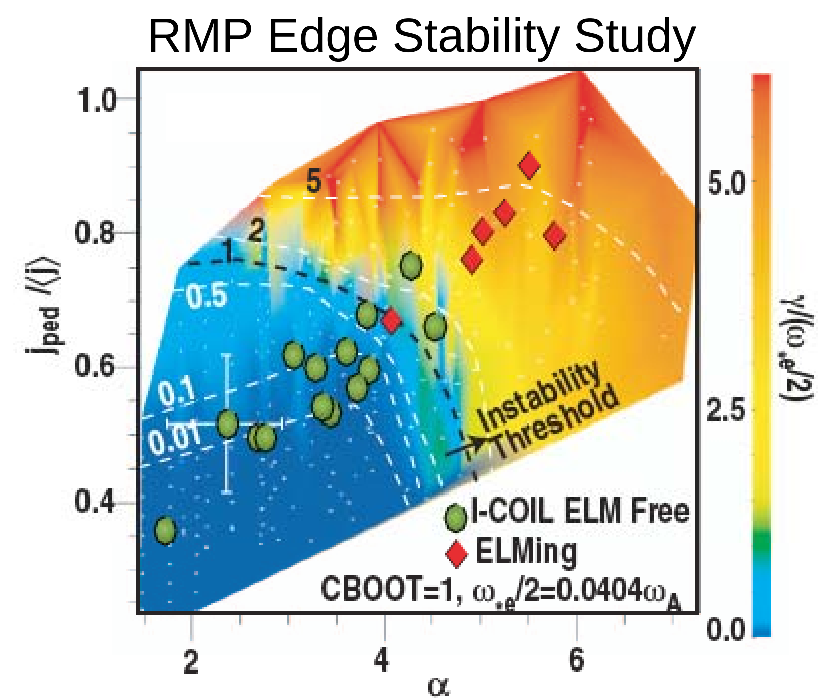
Peeling-Ballooning Model Offers Insight on Understanding ELM-free regimes





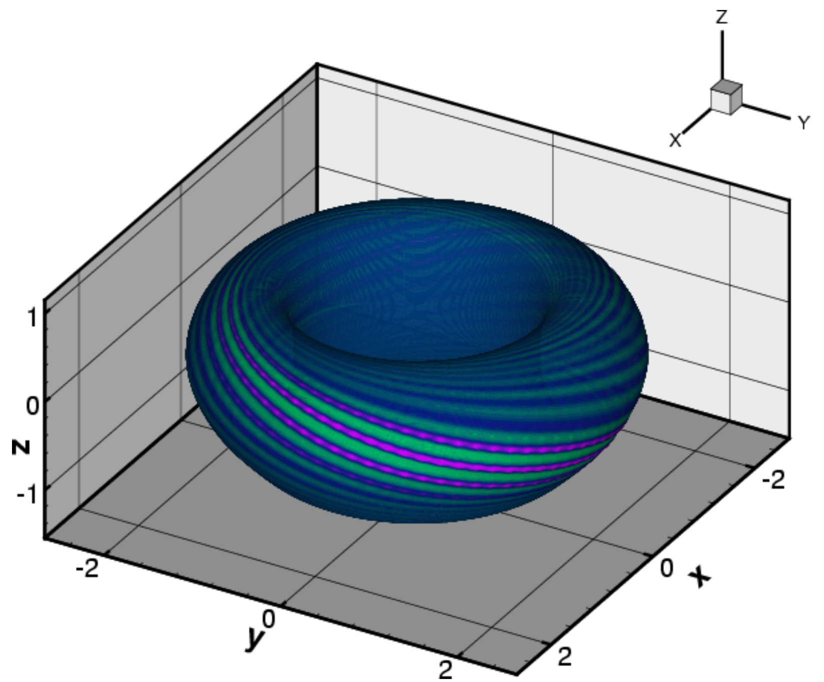
- **Peeling-Ballooning Model Validation successful in standard Type-I ELM regime**
- **QH-mode exists near kink-peeling boundary**
  - Allows accurate prediction of maximum density for QH mode -> expt planning
  - Model developed for understanding role of rotation and density in QH mode (IAEA 2006)
- **In the ELM-suppressed Resonant Magnetic Physics (RMP) regime, increased particle transport holds the pedestal below the peeling-ballooning stability limit**
  - Understanding transport in the presence of the RMP is key challenge

The NIMROD Project provides macroscopic modeling for burning-plasma-relevant studies.

[See http://nimrodteam.org for more information.]

⇒ ELM modeling for CPES contributes nonlinear modeling for the crash phase. [Lehigh, T-X]

- Disruption mitigation studies investigate important MHD mixing effects, now including impurity radiation modeling. [GA/UCSD]
- RF stabilization of tearing modes for SWIM will include kinetic closure effects in 3D magnetic fields. [U-WI, USU, Tech-X, ORNL, MIT, CompX]
- Simulation particle modeling of fast ions is being used for ion kinetics in kink and tearing modes. [U-WA, CU, U. Tulsa]
- Whole-device simulation, e.g., RFP, spheromak, etc. [U-WI, LLNL, U-WA]

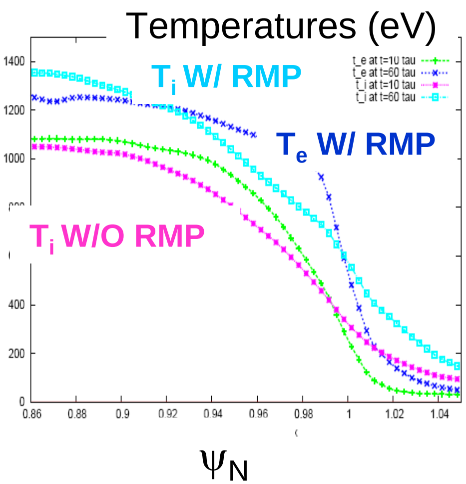


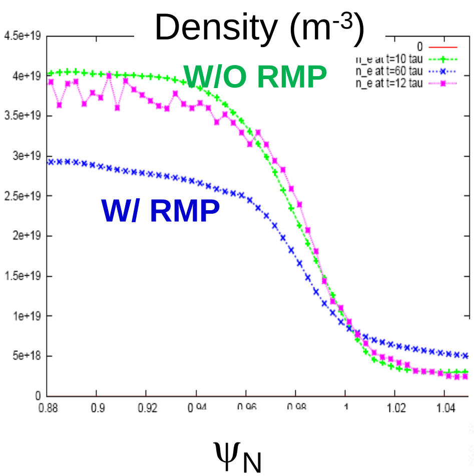
Temp. perturbations from nonlinear ELM simulation.

Using Resonant Magnetic Perturbations to control edge localized modes

- RMP is known to reduce edge density gradient, hence stabilize edge localized modes
  →Enables successful ITER operation without wall damage

- RMP physics is not well understood
  - Edge particle code XGC0 reproduces experiments (DIII-D)



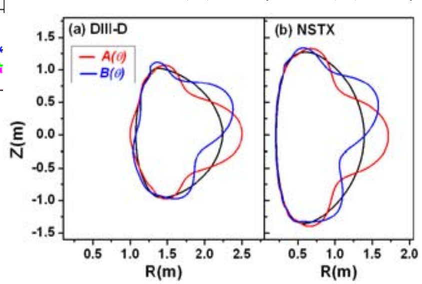


- RMP ≠Rechester-Rosenbluth
- $D_{RMP} < \chi_{RMP}$
- Heat flux from core keeps edge T_i &T_e up

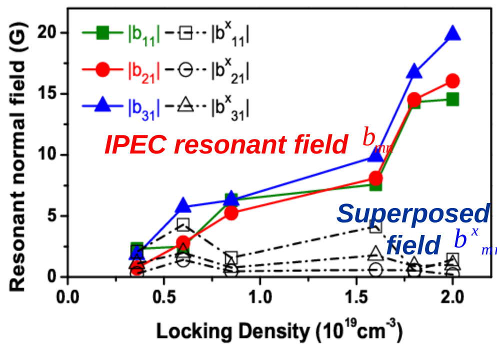
- Critical RMP shown to be proportional to the locking density when plasma response included
- For arbitrary external field on boundary, $\delta B^x \cdot \hat{n}$, IPEC (based on DCON and VACUUM) finds perturbed equilibria holding $q(\psi)$ and $P(\psi)$ fixed
- Shielding currents give driving resonant field b_{mn} for islands
- Empirically, critical $\delta B^x \cdot \hat{n}$ for island shielding is proportional to density and seen in IPEC.
- IPEC can find the optimized external field and coils by enhancing edge perturbation, but reducing core perturbation to control ELMs in ITER

The most sensitive field

$$\delta B^x \cdot \hat{n} = A(\theta)\cos\phi + B(\theta)\sin\phi$$



DIII-D Locking experiment



IPEC ref Park..(POP14,PRL99), Boozer..(POP13)

CPES/NYU

Columbia/PPPL

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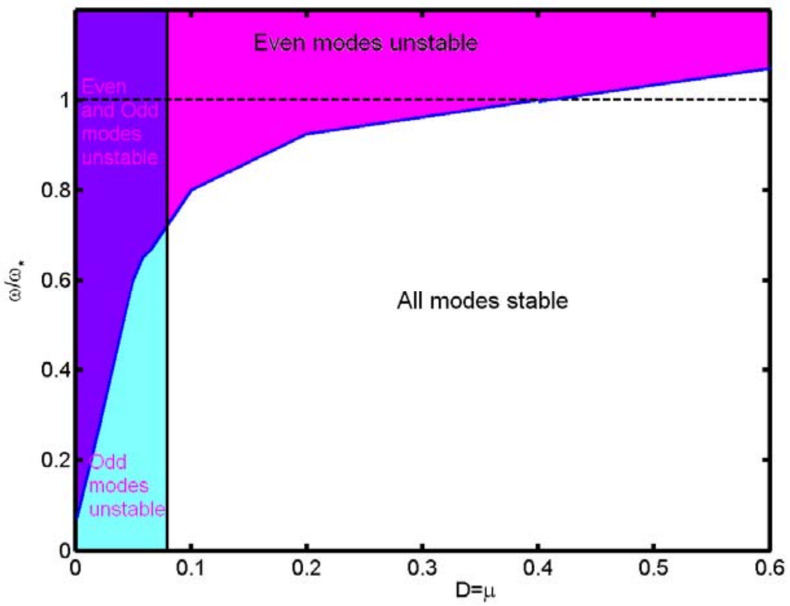
Analytical theory: Advances in the theory of neoclassical tearing modes

- Neoclassical toroidal viscosity (due to non-resonant nonaxisymmetric **B** fields) was shown to modify the field error penetration threshold in Ohmic tokamaks. Theory reproduces the empirical density scaling for critical error field penetration (Cole, et al, PRL '07).

- Analysis of the effect of turbulence on islands (IFS: Waelbroeck, et al)
  - Islands arise due to neoclassical tearing modes
  - Island rotation matches local electron diamagnetic frequency (frozen-in electrons).
  - Density flattening stabilizes the turbulence and slows the island rotation, increasing the stabilizing polarization current.



  - Turbulence can be switched on/off by enforcing parity
  - Turbulence causes transitions to more slowly rotating state that are more stable

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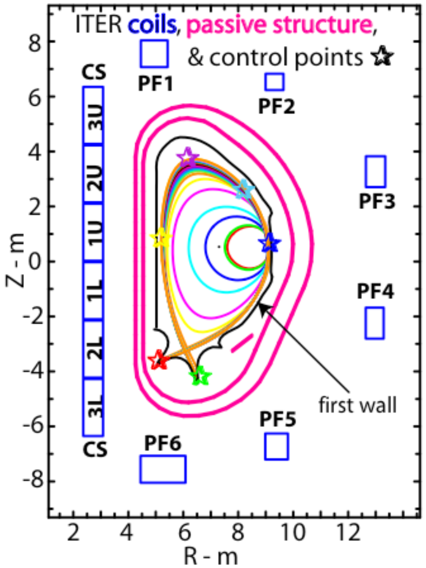
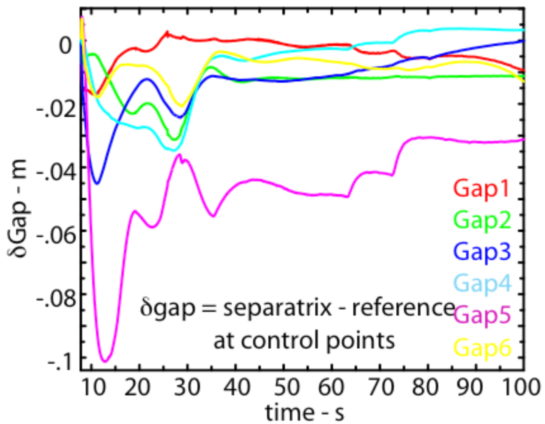
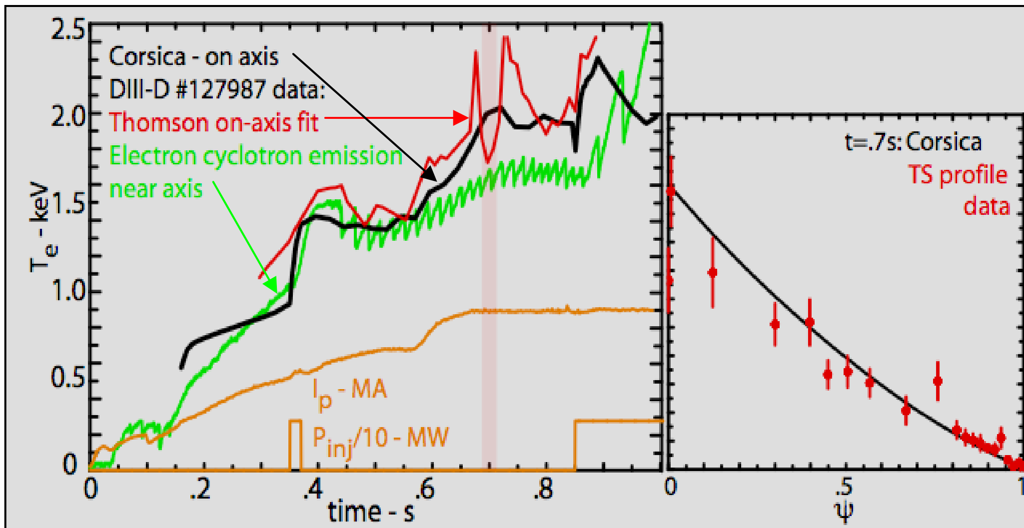
CORSICA and TSC modeling is contributing to resolution of ITER design issues: coil system and controller capability





- **ITER free-boundary simulation with $T_{e,i}$ evolution (CORSICA)**
  - ITER VS1 controller
  - Small-bore scenario-2 (Gribov)
  - Small δgap measurements ⇒ controller achieved scenario
- **CORSICA VS1 ability to control vertical instability and displacement events has been assessed.**



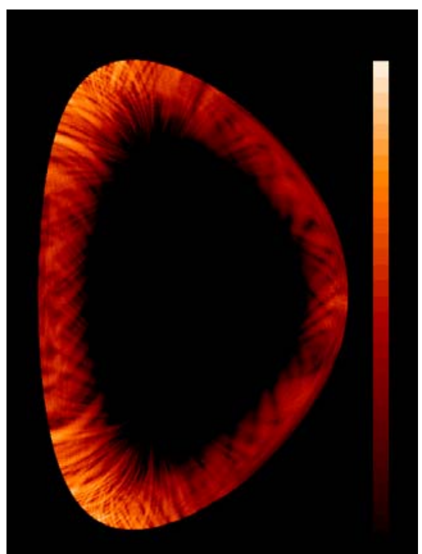
- **CORSICA transport validation from DIII-D ITER startup experiments**

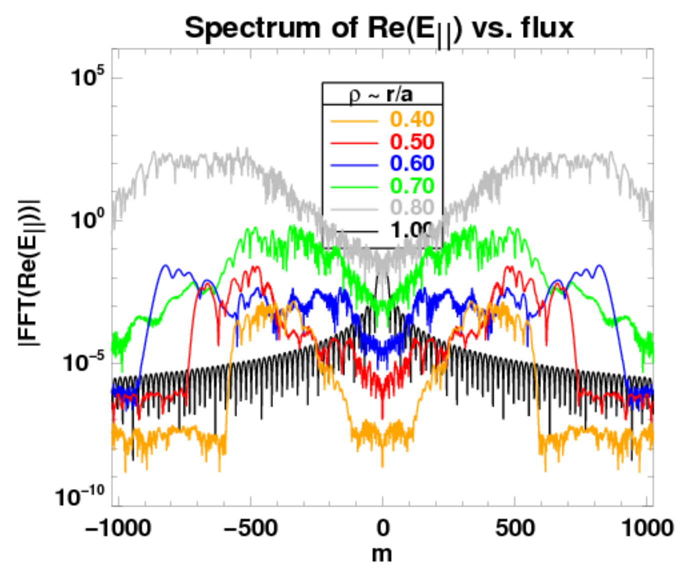
LLNL, PPPL

Full-wave Lower Hybrid Simulations with Parallel Code TORLH

- Diffraction and focusing effects now fully resolved
- Using the new PSFC Beowulf cluster, Loki, MIT has simulated full scale Alcator C-Mod LH experiments
- Satisfies 2008 Joule Theory Milestone
- Iteration with a Fokker-Planck code(CQL-3D) will require leadership class computer

Re{$E_{||}$} contours and associated spectrum





MIT

Modeling of ICRF Heating and Current Drive in ITER

- Ion Cyclotron Range Radio Frequency heating (ICRF) is one of the principal means for heating the ITER plasma to fusion temperatures.
- The visualization shows the ITER vacuum vessel and ports (gray), the ICRH antenna (~2m in height, red), and the time-dependent magnitude of the fields $\mathrm{Re}\,\vec{E}_{\perp}$
- ICRF also will be used to drive current in ITER. The required directionality can be seen in the "green" waves that propagate clockwise toroidally.
- This visualization of the 3D ICRF fields calculated by the AORSA simulation on the CCS Jaguar XT4 under an INCITE award.

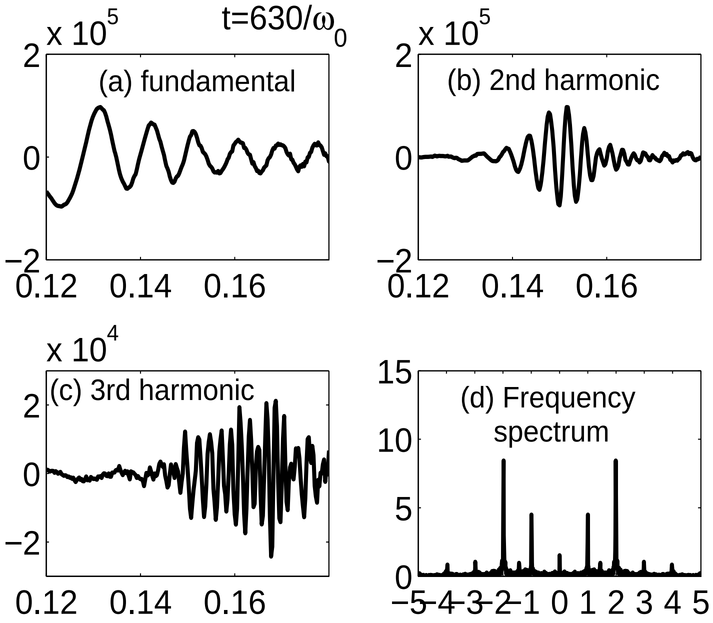
see movie “raytraced.mp4”

Computation and theory identified important nonlinear EBW effects

- Computational study of EBW showed generation of strong second harmonics
- Computation required development of implicit δf to reduce simulation noise, take long time steps
- Followup theory showed that harmonic generation significant at proposed power levels

75 kW in S-band waveguide;
E = 1.5e5 V/m
nT = 10^{17} x 200 eV/m^3
$(1/2)\varepsilon_0 E^2/nT = 3\times10^{-2}$
Difficult regime for full PIC

E_x for different modes



U. Colorado/Tech X

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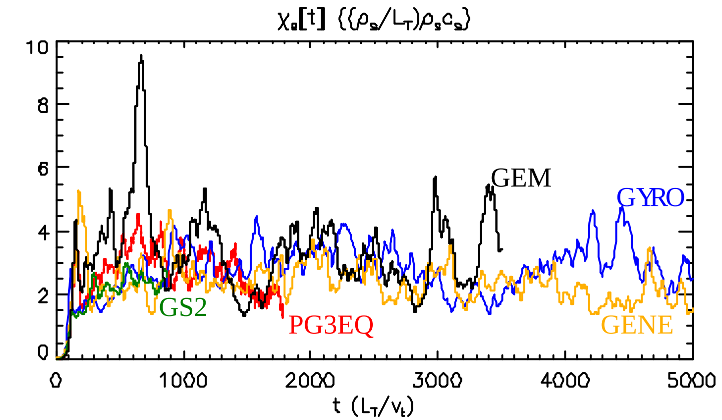
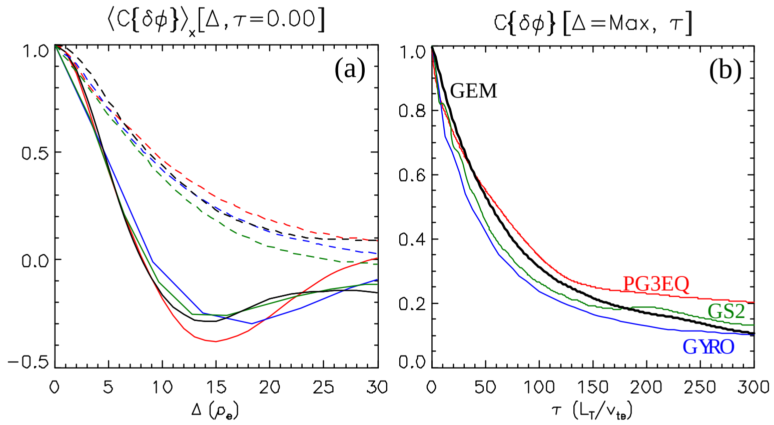
Code Verification: ETG Turbulence Simulations from 5 codes

agree in magnitude of heat flux and in structure of turbulent fluctuations

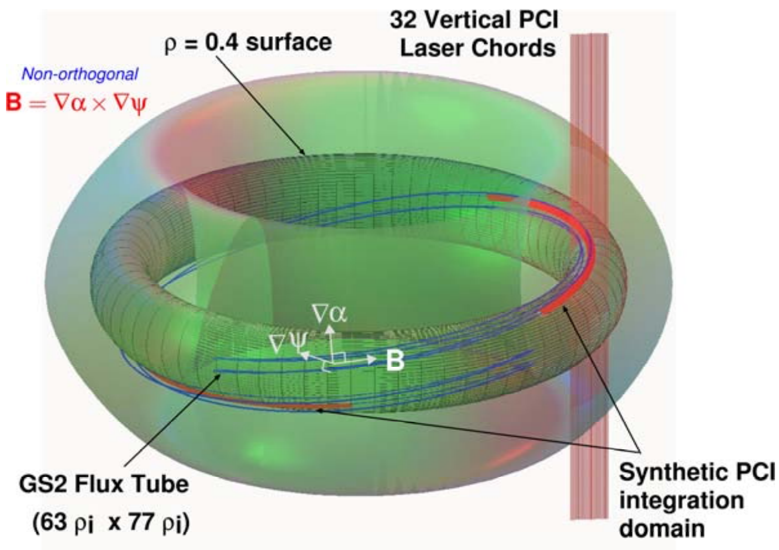
- Gyrokinetic simulations addressing importance of ETG to ITER-relevant core plasmas
- Benchmarking with
  - GYRO
  - GS2
  - GEM
  - PG3EQ
  - GENE
- Codes agree about
  - The magnitude of χ_e
  - The intensity of the turbulence
  - The structure of the turbulent correlations in space and time
  - The *rms* ExB shearing rate
- See Nevins, Parker, Chen, Candy, Dimits, Dorland, Hammett, and Jenko, Phys. Plasmas **14**, 084501 (2007).

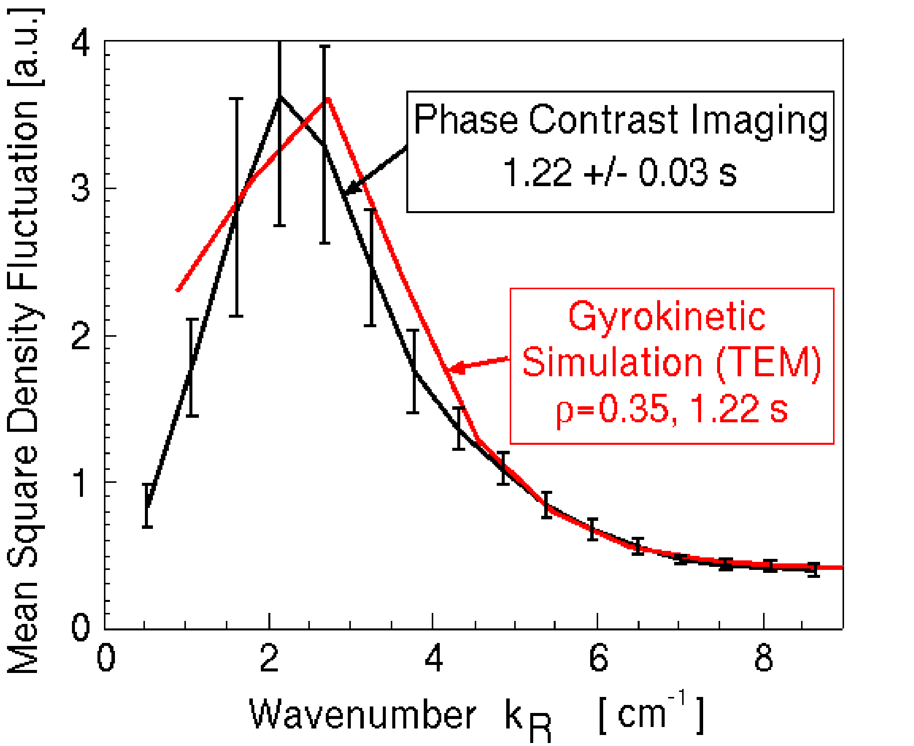




Code Validation: Synthetic Diagnostics Enabled Comparison of Nonlinear Gyrokinetic Simulations with Measured Fluctuations

- First of kind comparison
- Measured wavelength spectrum closely reproduced by GS2
- Direct evidence of trapped electron modes in Alcator C-Mod ITB

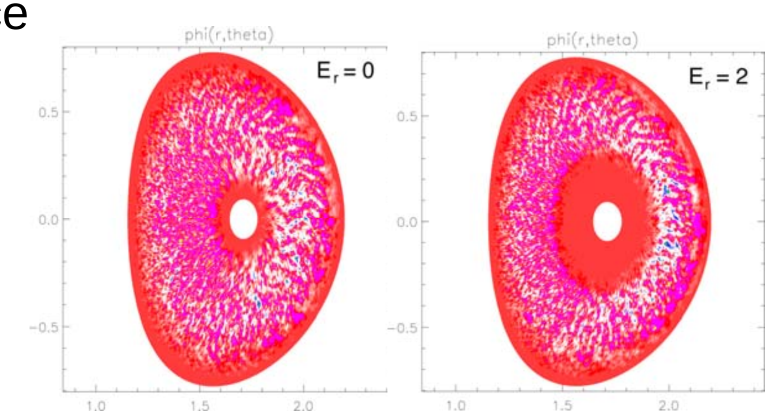




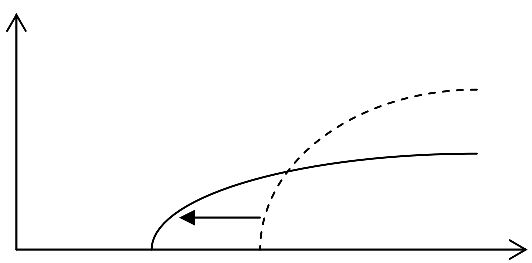
D. R. Ernst et al., IAEA-CN-149/TH/1-3 (2006). Submitted to Phys. Rev. Lett.

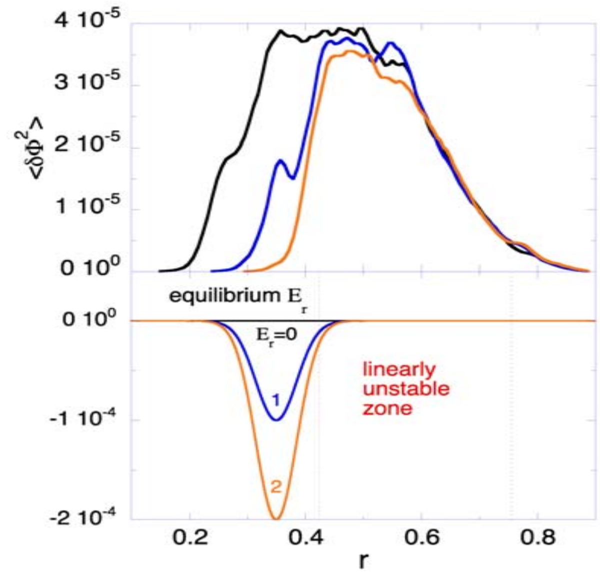
Turbulence spreading is reduced by ExB shear

GTC-S nonlinear simulation of ITG turbulence exhibits significant turbulence spreading into the linearly stable zone
[Wang, Hahm, Lee et al., PoP 14, 072306 '07]



With ExB shear, spreading extent, Δ is reduced as expected from nonlinear diffusion model
[Hahm, Diamond, Lin et al., PPCF 46, A323 '04]:



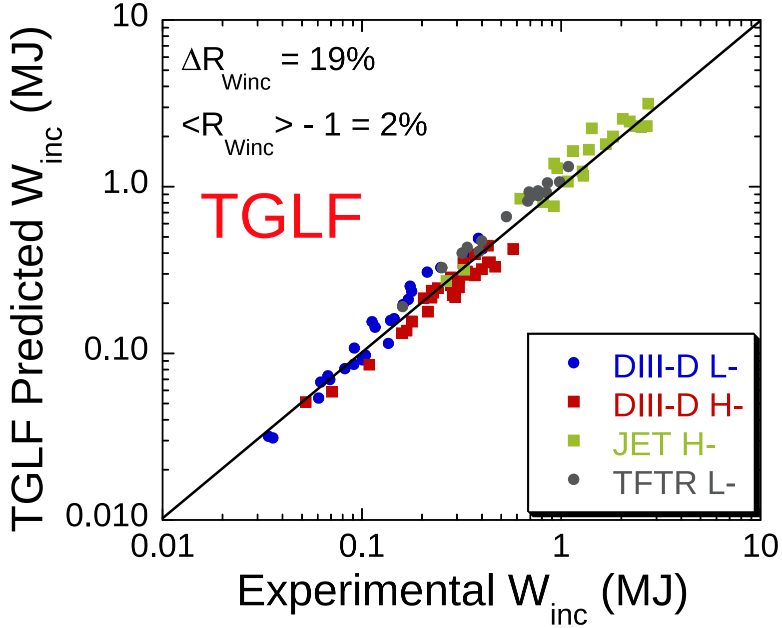


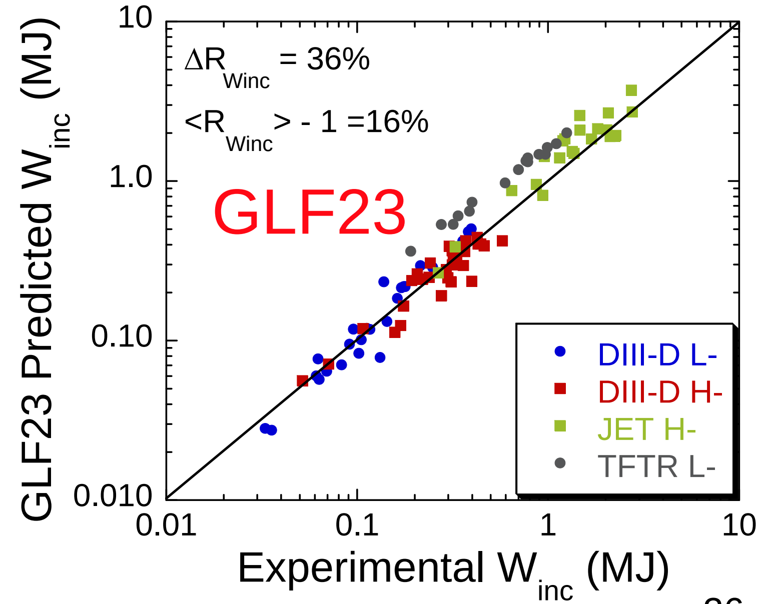
Balancing propagation time to damping time,
$\Delta / V_s \sim 1/|\gamma'|\Delta \Rightarrow \Delta \sim (V_s / |\gamma'|)^{1/2}$
ω_{ExB} increases damping rate slope $|\gamma'|$ and reduces fluctuation intensity locally.
Spreading speed V_s gets reduced with fluctuation intensity.

Reduced Models to Simulate Tokamak Discharges:

TGLF accurately reproduces linear GK growth rates and turbulent transport

- TGLF solves for eigenvalues using 15-moment GF eqs, 11% avg error in linear growth rate
  - Uses analytic theory to allow efficient and accurate numerical calculations
- Model of nonlinear saturation levels developed for shaped geometry; fit to GYRO results
  - Improves on GLF23 with shaping, accurate trapped particle effects, finite-beta, valid continuously from low to high-k
- Tested in database of DIII-D, JET and TFTR discharges:
  - Avg RMS error in W_{tot} is DR_{Wtot}=10% for TGLF, 20% for GLF23; Offset in W_{in} smaller for TGLF (2% vs 16%)





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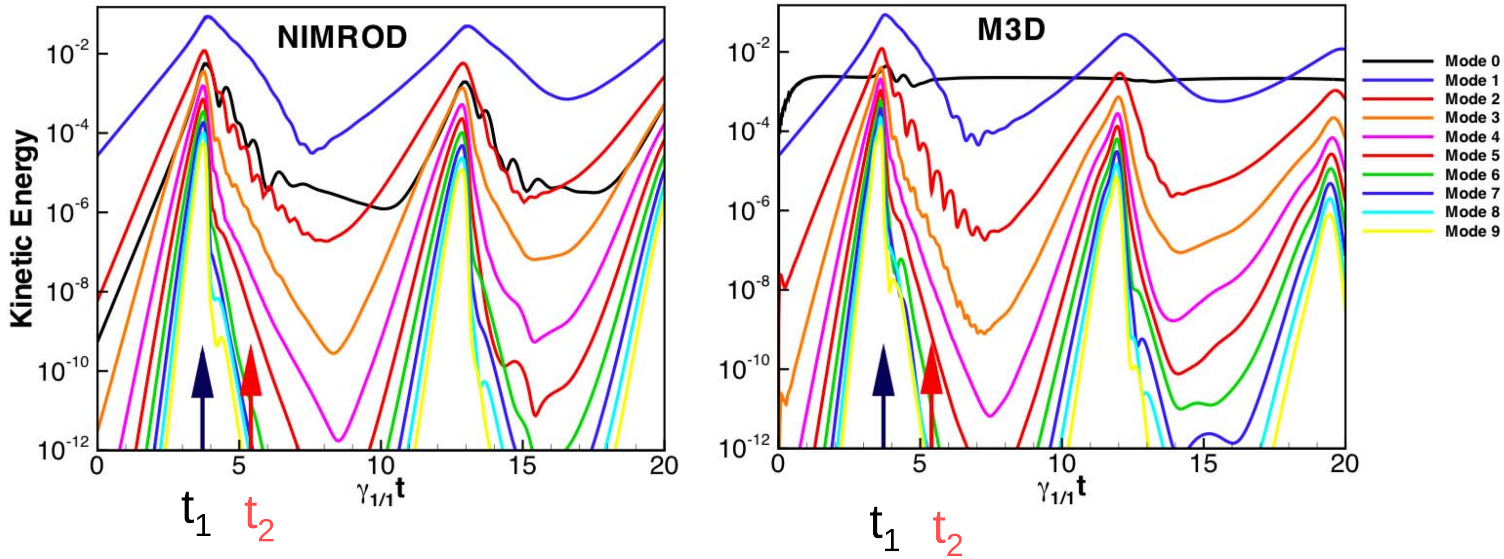
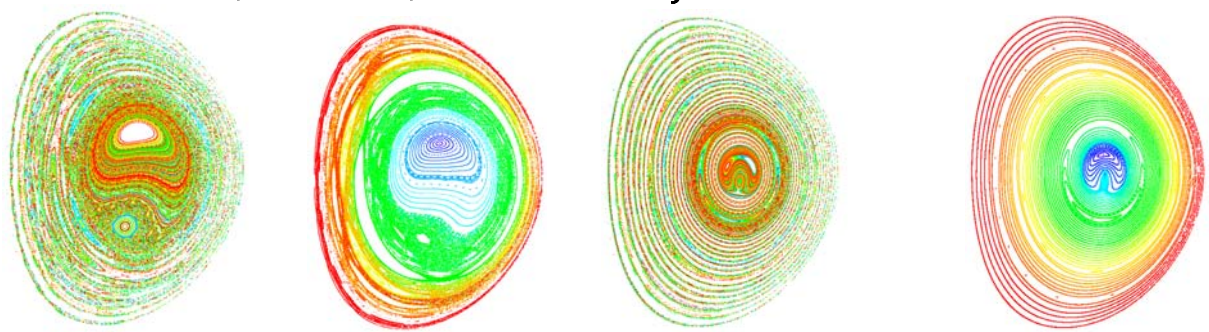
M3D and NIMROD 3D MHD Codes have successfully completed a major nonlinear verification and validation test: Sawtooth activity CDX-U.



- Figure shows kinetic energy vs time the first 10 toroidal modes for NIMROD and M3D with same initial conditions, sources, and boundary conditions

Flux surfaces (Poincaré plots)



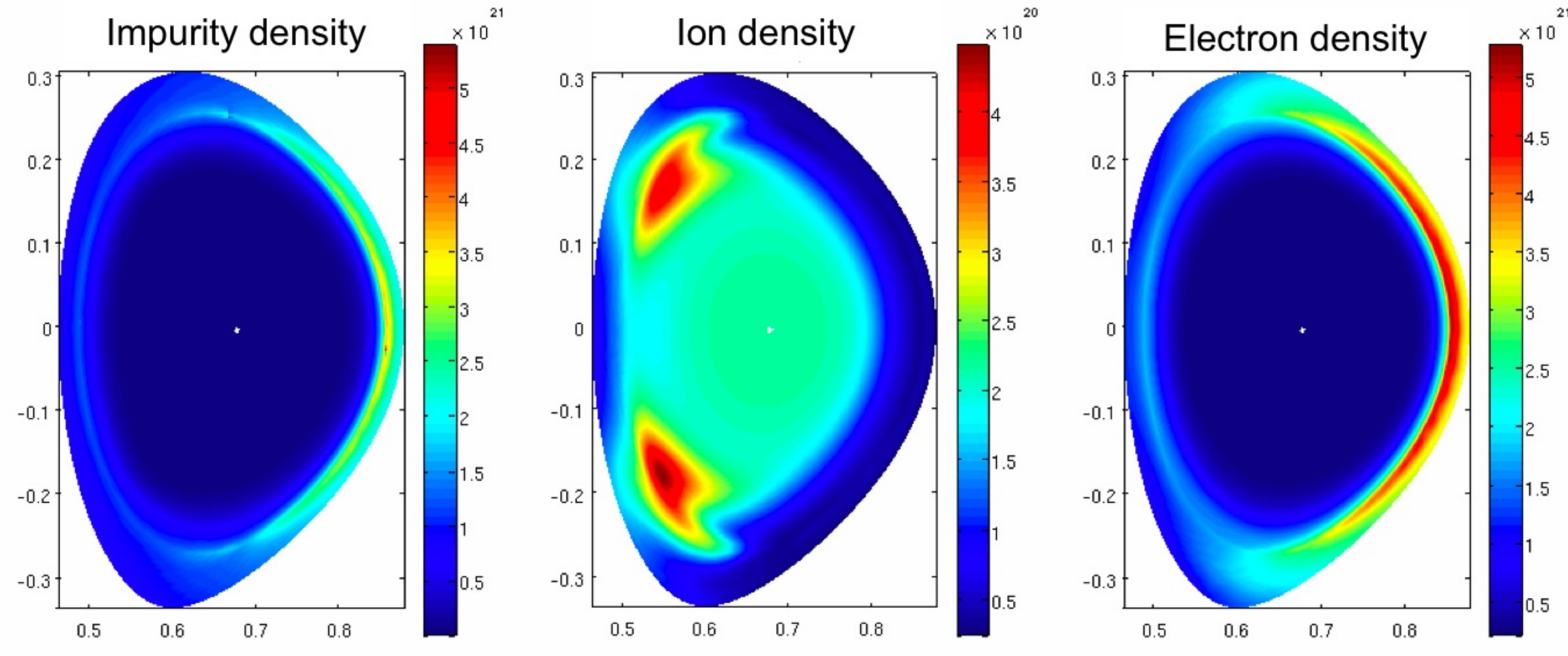
$t=t_1$ (M3D) $t=t_1$ (NIMROD) $t=t_2$ (M3D) $t=t_2$ (NIMROD)

- Initial series included non-physical “source terms” to maintain profiles. New series uses Ohmic heating and loop voltage boundary conditions, and spatially varying thermal conductivity. Now matches experimental sawtooth period to within 10%

The NIMROD Project provides macroscopic modeling for burning-plasma-relevant studies.

[See http://nimrodteam.org for more information.]

⇒ Disruption mitigation studies investigate important MHD mixing effects, now including impurity radiation modeling. [GA/UCSD]



Radiation modeling for disruption mitigation studies uses the KPRAD code and three separate densities.

Many exciting burning plasma research challenges exist now

National Academies NRC Burning Plasma Report

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- Understand dynamics of edge Pedestal region
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- Stabilization of neoclassical tearing modes
- Develop steady-state & advanced tokamak regimes
- The density limit and high density operation
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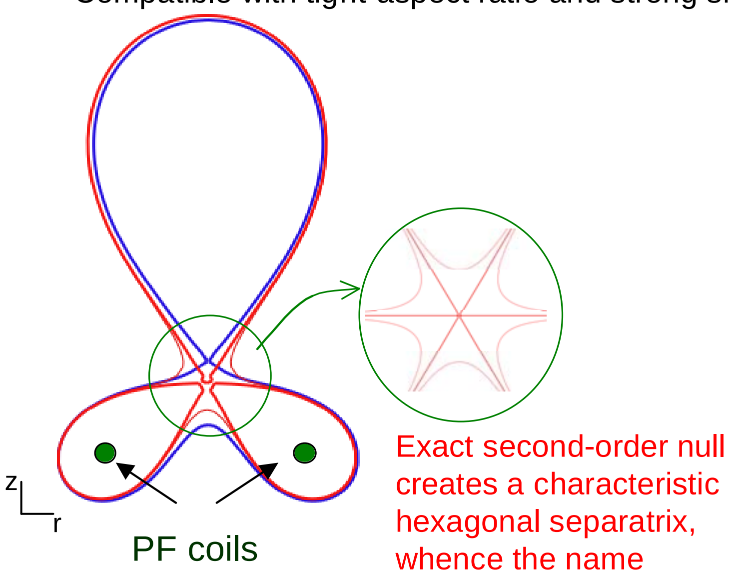
$\Rightarrow$ Divertor science & technology development

- Energetic particle issues

Research on Advanced Divertor Concepts

Snowflake divertor to reduce heat load:

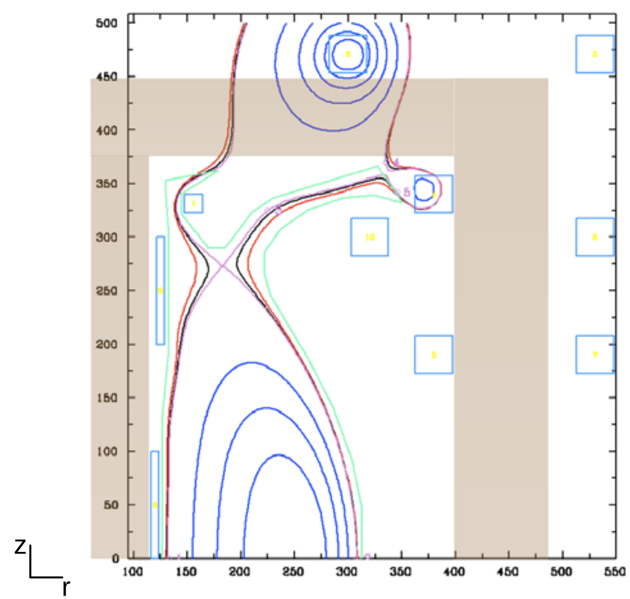
- Strong flux expansion near the null-point/divertor as $B_p \sim r^2$
- Configuration can be created by simple set of PF coils situated <u>outside the TF coils</u>
- Increased shear just inside the separatrix provides an additional "knob" for ELM control
- Blob transport outside the separatrix is reduced
- Compatible with tight-aspect ratio and strong shaping



* D.D. Ryutov. Phys. Plas., **14**, 064502, (2007); D.D. Ryutov, R.H.Cohen, T.D. Rognlien, M. Umansky. To be presented at the Sherwood Theory Conference, Boulder, 2008.

Super XD moves the divertor plates to larger major radius

- Increases wetted area by ~ 2-3
- Increase line length by a factor of 5 -10
- Longer line length increases intrinsic SOL width for same SOL physics by ~ 1.5-2
- Net: increases divertor heat capacity by ~ 5
- Similar factor of improvement applies to transient ELM and disruption heat pulses
- Enables AT reactors and requires simple PF coils with small currents



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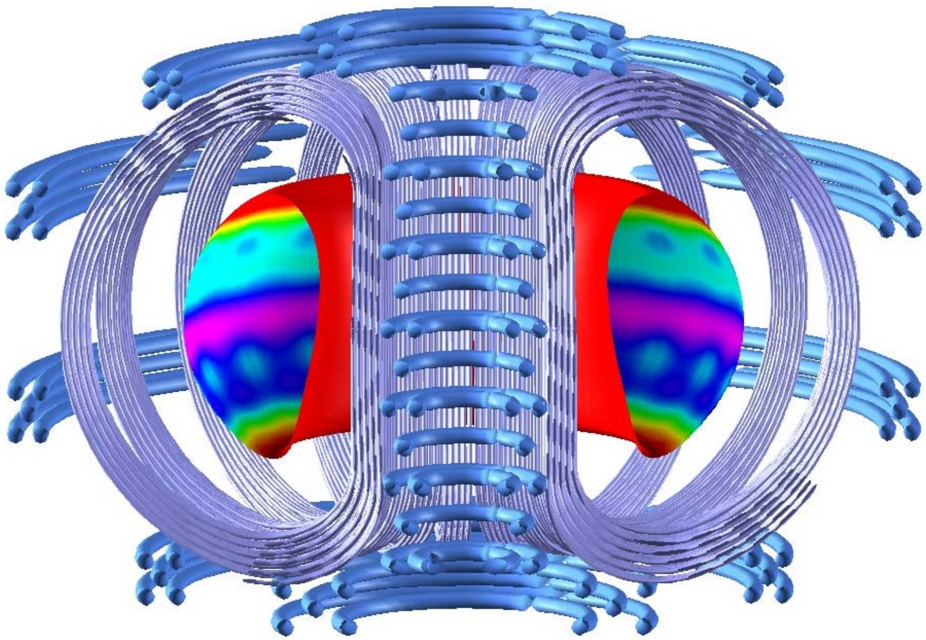
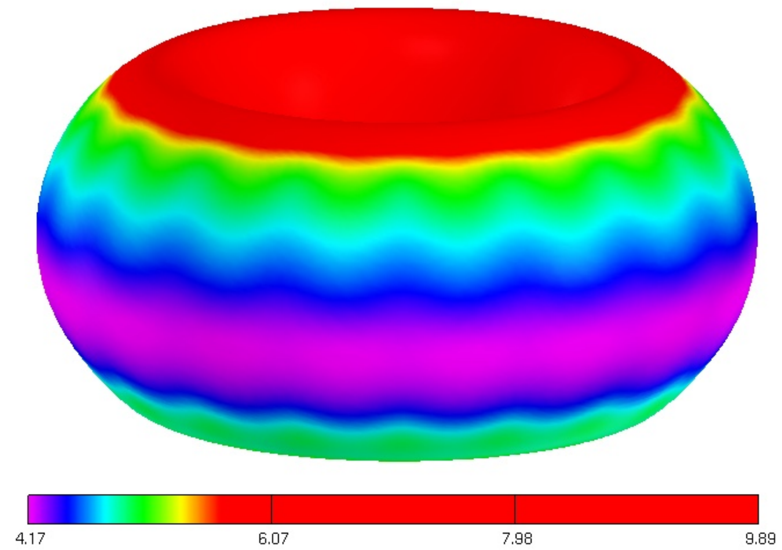
$\Rightarrow$ Energetic particle issues

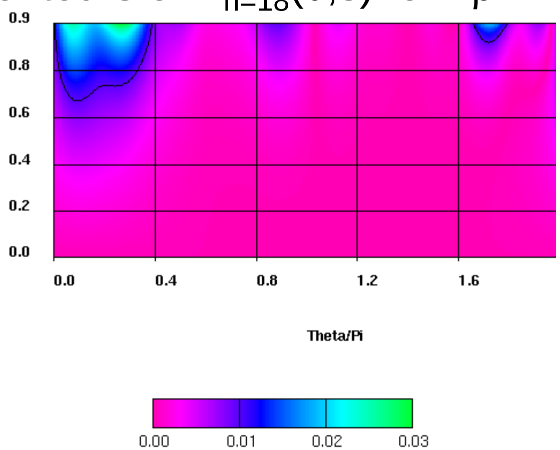
ITER 3D VMEC equilibria include finite β amplification effects on ripple strength for α orbit loss calculations



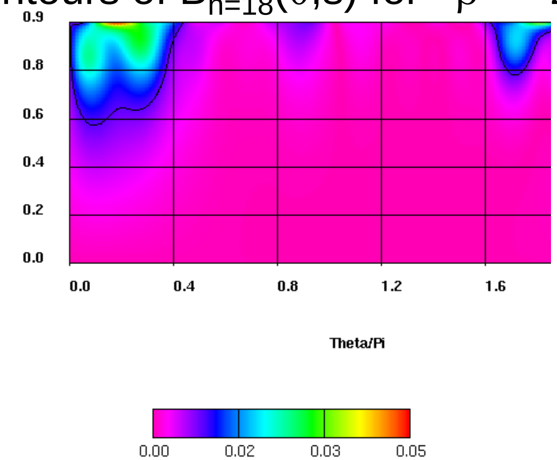
|B| contours on outer flux surface (compressed color map)



Contours of $B_{n=18}(\theta,s)$ for $<\beta> = 0\%$



Contours of $B_{n=18}(\theta,s)$ for $<\beta> = 2.4\%$



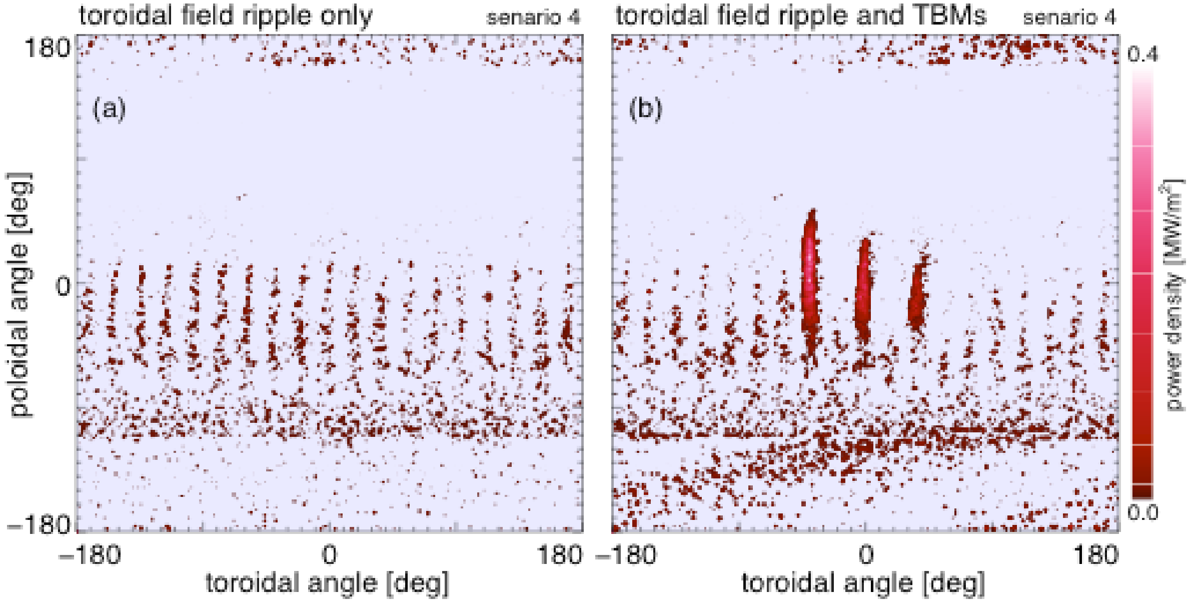
Calculation of Alpha Particle Orbits in ITER

· Alpha particle loss in ITER studied with and without the test blanket modules (TMB)

· The numerical equilibrium and ripple data were obtained from the ITER data base. The ripple is given by partially optimized field coils.

· The full Lorenz orbit SPIRAL code used to calculate the alpha particle loss distribution at the plasma boundary and the guiding center code ORBIT, which can perform much longer simulations, to estimate the total losses.

· Significant hot spots appear especially during low current high q operation.

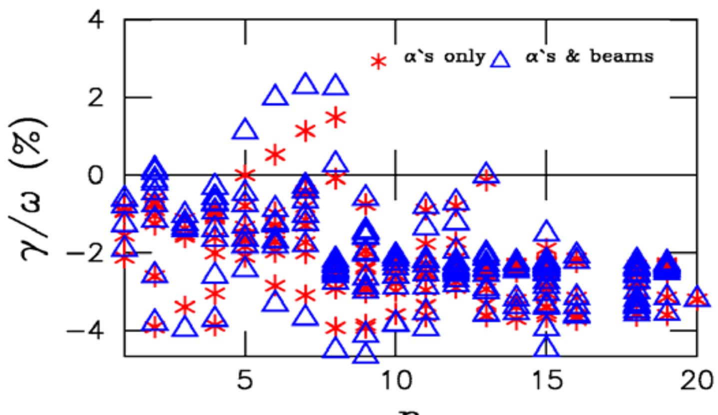


FY07 Joule Milestone on ITER Alfven mode stability

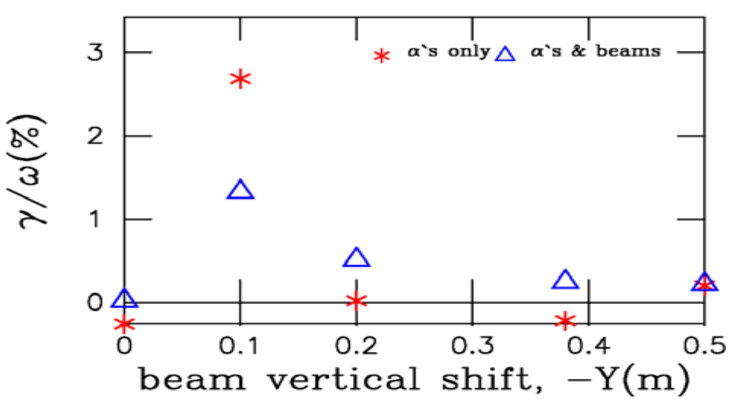
- *PPPL led team (+ IFS, MIT, Irvine, and ITER) succesfully met the milestone: NOVA-K was used to analyze low-to-high-n TAE stability in ITER-representative plasmas: H-mode(normal shear), hybrid and AT.*
- *NBI distribution model that was used is in good agreement with TRANSP Monte-Carlo model*

Main results:

- *Beam ions contribute as much as fusion alphas to TAE growth rate.*
- *Normal shear is marginally unstable; hybrid and AT plasmas are unstable due to high q values and strong NBI pressure gradient at r/a=0.5; AT is most unstable.*
- *AE stability control is possible by changing the NBI injection angle (right figure): on-axis and strongly off-axis NNBI are stabilizing; slightly off-axis (10-20cm vertically) NNBI yields the most AE-unstable plasmas.*



Most TAE unstable AT plasma vs. mode number

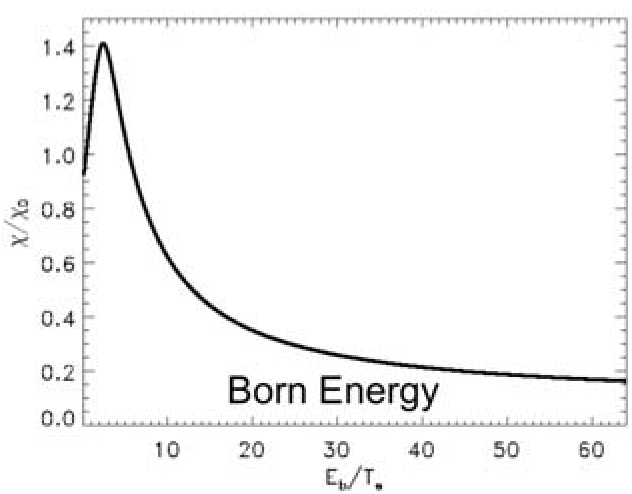


NNBI aiming helps to control TAE stability

New nonlinear gyrokinetic (GKM, M3D based) code is being developed for high-n (up to ~40) TAE simulations.

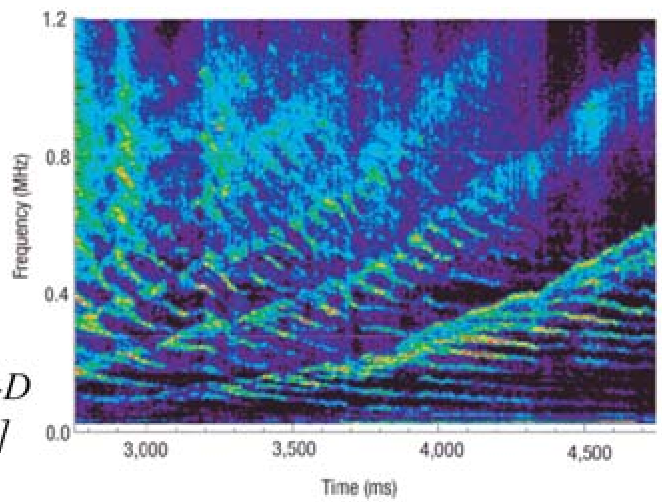
Gyrokinetic Simulation of Energetic Particles

- Energetic particle (EP) turbulence & transport in ITER requires kinetic simulation
- Progress of gyrokinetic PIC GTC & continuum GYRO simulations of EP
  - EP transport by microturbulence decreases as EP energy increases
  - Excitation of toroidal Alfvén eigenmode (TAE) by EP radial density gradients
- SciDAC GSEP: *Gyrokinetic Simulation of Energetic Particle Turbulence and Transport (*PI: Z. Lin, UCI, GA, ORNL, UCSD, and LLNL)
- 2008 Hannes Alfvén Prize to be awarded to Liu Chen (UCI) at EPS for his work on Alfvén waves and EP physics



Gyrokinetic simulation of NBI diffusivity by microturbulence

Spectrum of Alfvén eigenmodes in DIII-D [Nazikian et al, PRL06]



Code Validation: "True" & Quasimodes in Alfvén Cascade on JET

Alfven Gap in LAPD

- Alfvén Cascades concentrate at the point of shear reversal, where the system is "most uniform". Their structure is less robust than their frequencies.
- Alfvén Cascades with downward frequency sweeping represent quasimodes rather than "true" eigenmodes.
- The theory explains the "mystery" of downward sweeping.

IFS-JET collaboration, 2007

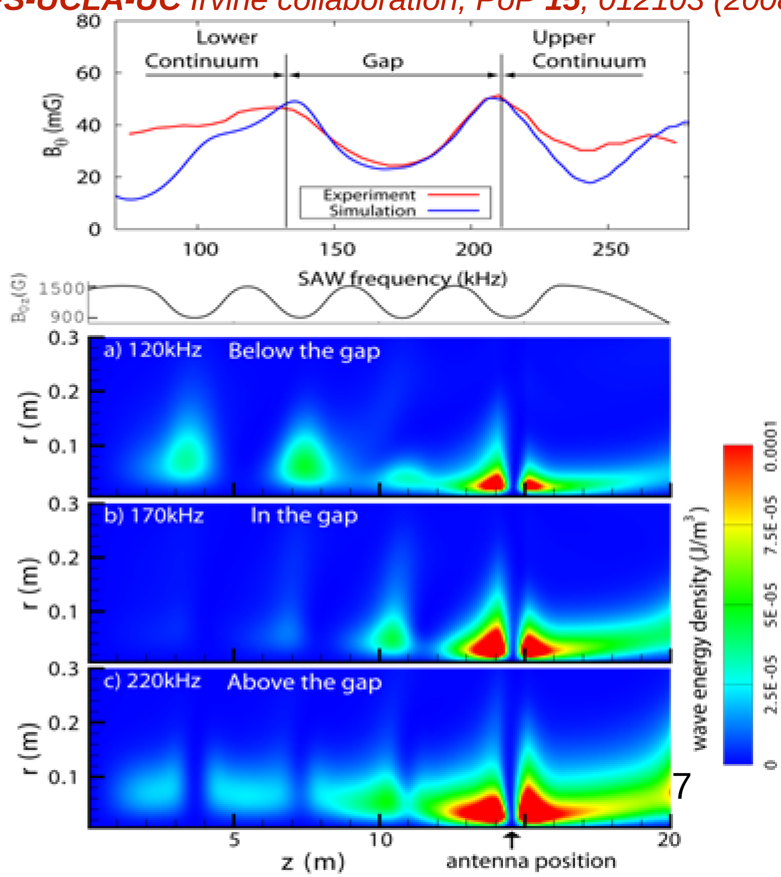
Quasimode

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

"True" mode

- Multiple mirror configuration in LAPD produces an observable spectral gap due to Bragg reflection.
- Standing Shear Alfvén wave is observed at gap frequencies.
- The IFS code reproduces spectral gap and wave propagation pattern.

***IFS-UCLA-UC** Irvine collaboration, PoP **15**, 012103 (2008)*



OFES theory program addresses most of the NRC burning plasma research opportunities

Jim Van Dam, 2007 APS DPP Tutorial

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- The density limit and high density operation (no slide, but covered)

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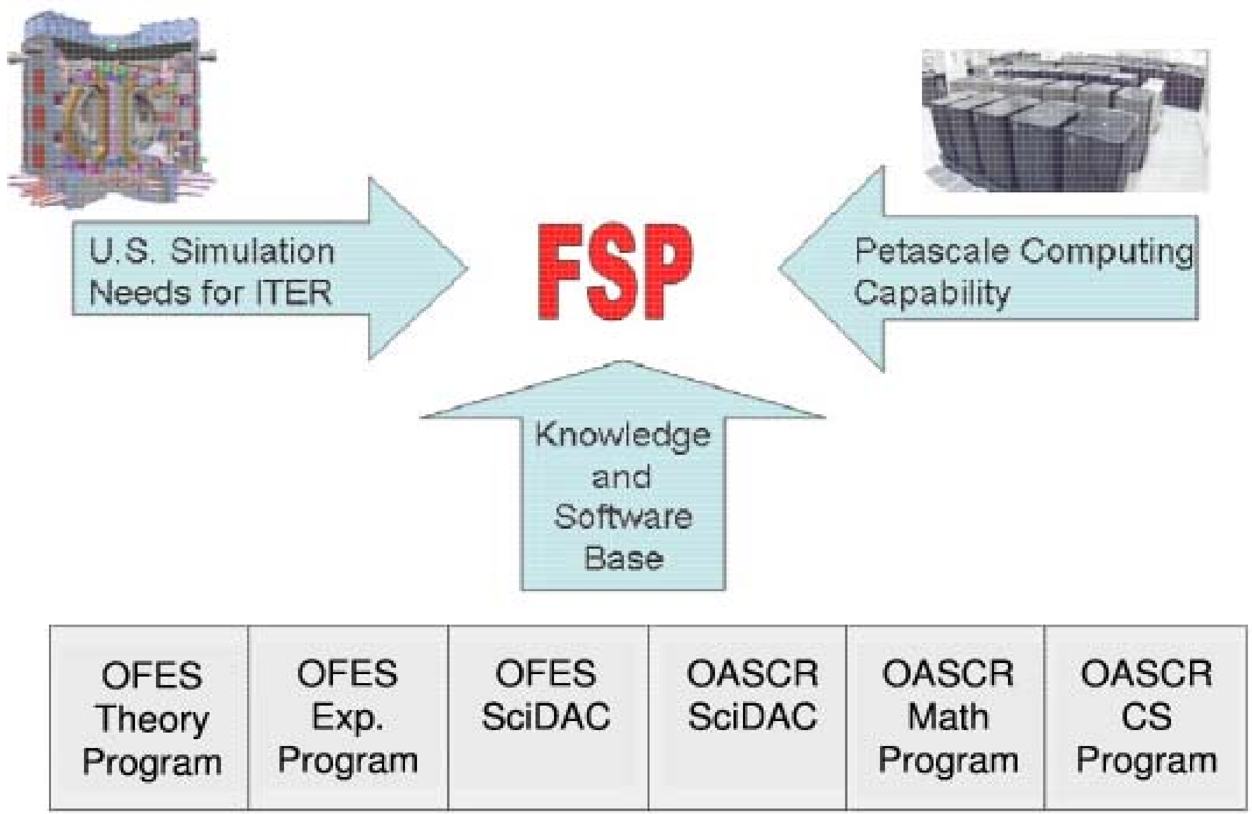
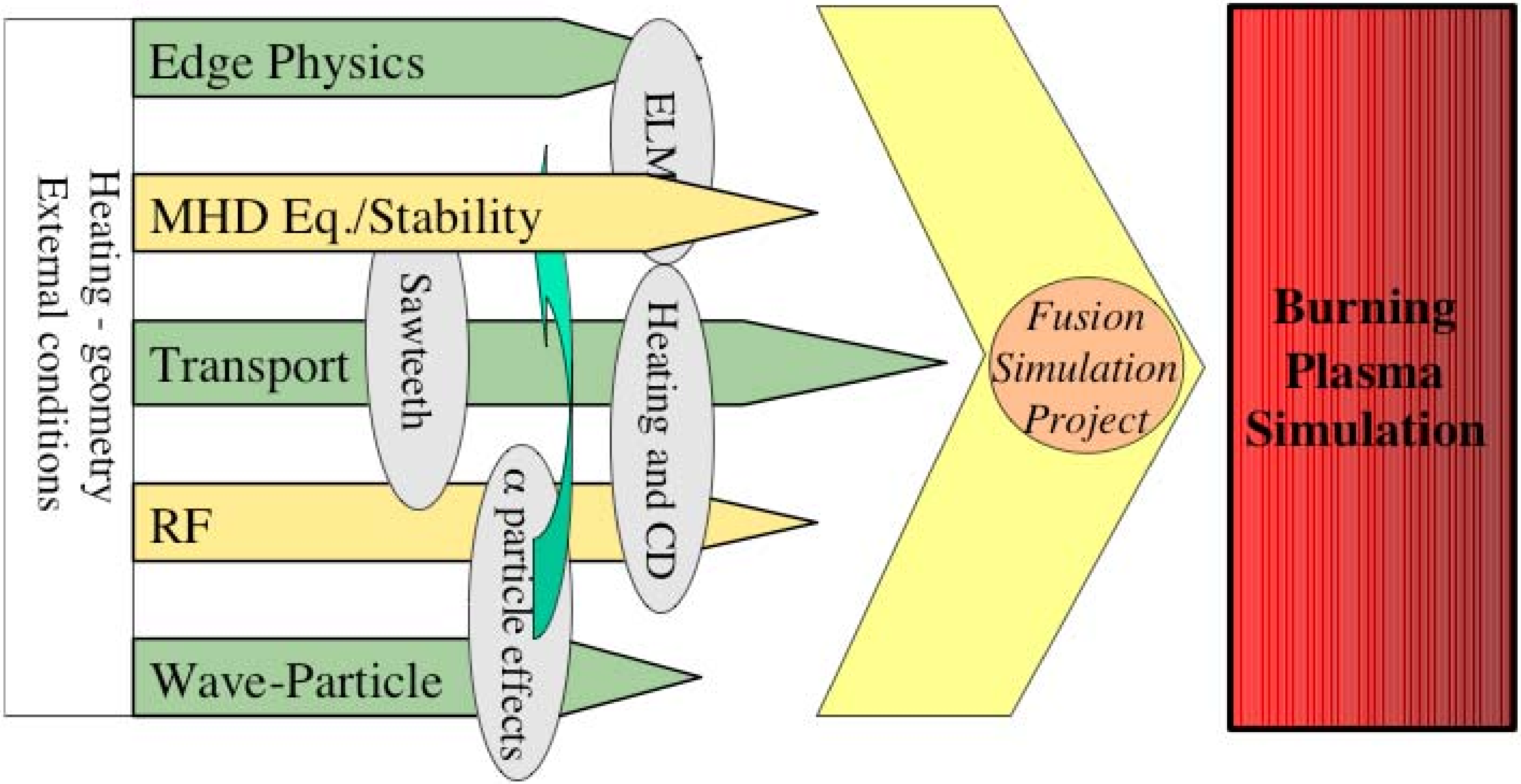
⇒ Energetic particle issues

Driving Forces for Fusion Simulation Project

- There are three driving forces for FSP:
  - Urgent need for a burning plasma simulation capability
  - Emergence of petascale computing capability
  - Knowledge and software that has been assembled under OFES and OASCR research programs



Fusion Simulation Project could provide the tools for connecting the continuously updated packages for all the topical areas



Collaborative Projects in Integrated Modeling: FACETS, PTRANSP, SWIM, CPES, etc.

- PTRANSP is the TRANSP analysis code used for predictive integrated modeling simulations
  - Carry out tasks that support SciDAC FSP prototype projects
- Recently added capabilities:
  - Newton's method for numerically stable predictions
  - Choice of TEQ, ESC and other equilibrium solvers
  - Predictive pedestal model, toroidal momentum transport (GLF23 or Weiland), Porcelli sawtooth model
  - ELVis web-based graphical display, object-oriented data structure, code steering
  - Upgraded NBI and RF heating and current drive sources
- New capabilities being added:
  - Predictive particle transport, free-boundary TEQ equil. module + generalized Ohm's law, TGLF to supercede GLF23, new Weiland transport model, ELITE code, TGYRO, …

- FACETS project aimed at bringing power of high-performance computation to integrated modeling: core-edge-wall coupling
  - Faster turnaround
  - Less-reduced models
- Progress
  - Parallel core solver
  - Parallel coupling to edge computations
  - FACETS-ASTRA comparing well
  - FACETS achieving 10x speed improvement through parallelism

- Other projects addressing integrated modeling: SWIM, CPES, …

U. Col., Tech-X, LLNL, PPPL, General Atomics, Lehigh, ORNL, NYU, …


SIMMS